Physical Forcing of Phytoplankton Population Abundance in the Gulf of Maine - Georges Bank Region

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LONG-TERM GOAL

The goal of this study is to understand the physical-biological interactions that control phytoplankton distributions observed in the Gulf of Maine / Georges Bank region.

OBJECTIVES

Realistic three-dimensional regional simulations of phytoplankton biomass which resolve time scales from hours to seasons and spatial scales ranging from 1 to 100km will be created. We will begin by establishing the large-scale, low frequency context with an investigation of the role of the climatological circulation in controlling regional-scale seasonal variations of phytoplankton abundance. This will set the stage for high-resolution data-driven simulations in the Western Gulf of Maine and on Georges Bank. Once validated, the numerical solutions will be used as a basis for diagnosis of the physical-biological mechanisms responsible for producing spatial and temporal variability in phytoplankton abundance. In particular, the influences of buoyant river plume dynamics and wind-driven coastal upwelling/downwelling are to be examined in the western Gulf of Maine. On Georges Bank, we will focus on the complex interaction of tides, baroclinic circulation, and wind-driven currents in generating phytoplankton patchiness.

APPROACH

(1) Use an adjoint data assimilation technique to infer the biological dynamics implied by seasonal changes in phytoplankton abundance and the climatological mean circulation.

(2) Formulate a simple biological model that captures the main ecosystem dynamics that control phytoplankton abundance.

(3) Apply the model in 1-D to the physical conditions in the Gulf of Maine to test the model's ability to simulate the observed seasonal cycles, and to get a basic understanding of the 1-D physical-biological interactions.

(4) Revise the biological model as necessary and calibrate the parameter values until satisfactory comparison with the observations is attained. Because the 1-D model does not include 3-D effects which contribute to the observed variations, we do not expect perfect agreement. However, this

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exercise will provide a biological model and set of parameter values suitable for use as a starting point for the 3-D simulations.

(5) Incorporate the biological model into the 3-D circulation models of the western Gulf of Maine (using ECOM-3D) and Georges Bank (using Quoddy).

(6) Conduct data-driven coupled 3-D simulations of phytoplankton biomass in the two regions, utilizing ECOHAB data in the western Gulf of Maine and Globec data at Georges Bank. SeaWifs imagery will be used in both regions as well.

(7) Diagnose from the simulations the key physical-biological interactions that control phytoplankton abundance and productivity.

WORK COMPLETED

In year one, we identified the need for a regional nitrate climatology suitable for initialization and specification of boundary conditions in the coupled model. Initial efforts aimed at constructing such a product directly from observations were thwarted by the lack of sufficient data coverage. This year we adopted a different approach that makes use of empirical relationships between nitrate and temperature/salinity characteristics derived for this region by Garside et al. (1996). Applying Garside et al.'s algorithms to the climatological temperature and salinity fields, we have successfully generated a nitrate climatology suitable for modeling purposes in this region.

Bi-monthly climatological chlorophyll distributions in this region have been compiled by O'Reilly and Zetlin (1996). Dr. O'Reilly kindly shared the results of this analysis with us, and we have mapped these distributions onto our model grids via objective analysis. These data were fed into an adjoint data assimilation procedure in which we infer biological sources and sinks implied by changes in abundance patterns and the underlying circulation. We have begun our analysis of these solutions to diagnose the processes controlling the seasonal mean phytoplankton distribution. Ms. Caixia Wang, a master's student in the MIT/WHOI Joint Program, carried out portions of this component of the work under the supervision of Dr. McGillicuddy.

We have also begun data-driven coupled simulations in the Western Gulf of Maine using ECOM-3D (a variant of the Blumberg and Mellor (1987) model). R. Signell designed the physical simulatin, which is also used for red tide simulations in this region (see http://crusty.er.usgs.gov/wgulf/wgulf.html). The simulation goes from 13 March 1993 to 1 June 1993, and is forced with observed, 3-hourly winds and buoyancy forcing. The biological model is a five compartment (nitrate, ammonium, phytoplankton, zooplankton and detritus) nitrogen-based formulation which was tested and calibrated against available observations (see last year's report). In our first set of experiments, nitrate, phytoplankton and ammonium were initialized based on data (mean March profiles), zooplankton were intialized as proportional to phytoplankton (one-tenth the phytoplankton concentration), and detritus as spatially constant.

RESULTS

Nitrate Climatology

An example of our nitrate climatology is shown in Figure 1. Mean temperature and salinity fields derived from all available hydrography in the region were obtained from the Dartmouth Numerical Methods Laboratory (http://www-nml.dartmouth.edu/); also see Lynch et al. (1996). Nitrate was diagnosed from these two variables based on formula TS from Garside et al. (1996). For the coastal waters shoalward of the 150m isobath, the resulting field appears reasonable (note that areas deeper than 150m, to which the algorithm does not apply, are blanked out). The main features of this nitrate distribution are broadly consistent with observations. Thus, we are satisfied that this climatology will be suitable for modeling purposes.

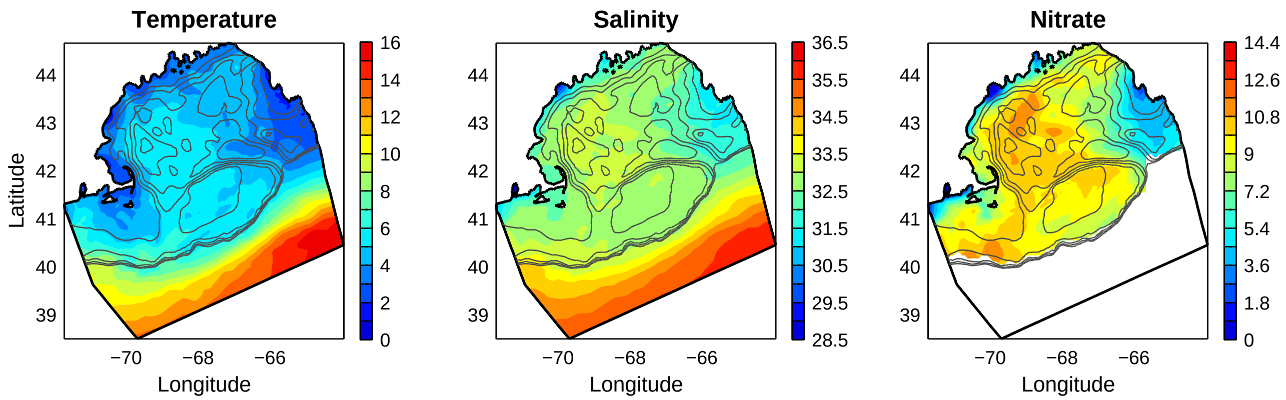

Figure 1. Surface temperature, salinity and nitrate for the January-February time period.

Regional-Scale Seasonal Variations in Phytoplankton

Our initial investigation into the large-scale seasonal variations in phytoplankton abundance in this region was based on an adjoint data assimilation technique. This approach was used by McGillicuddy et al. (1998) to study physical and biological controls on *Pseudocalanus* spp. distributions in this same region. The forward problem is posed as an advection-diffusion-reaction equation for organism concentration C:

$$\frac{\partial C}{\partial t} + \mathbf{v} \cdot \nabla C - \frac{1}{H} \nabla \cdot \left(HK \nabla C \right) = R(x, y)$$

where **v** is the velocity, *K* the diffusivity and *H* the bottom depth. The reaction term *R*(*x*,*y*) represents a highly idealized parameterization of population dynamics which varies in space only. Positive *R* implies net growth, while negative *R* implies net mortality. Specifying the climatological velocity and diffusivity fields, the adjoint of the advection-diffusion-reaction equation is used to invert for the population dynamics implied by changes in organism abundance and the circulation during the intervening period. This approach has proven to be successful with the climatological phytoplankton distributions mapped from the O'Reilly and Zetlin (1996) monograph. Preliminary results are described in Wang (1999). In short, the analysis has revealed geographically specific patterns in phytoplankton source/sink terms. These spatial patterns vary seasonally according to the phytoplankton distributions, the climatological currents, and their orientation with respect to each other. In cases when the flow is

either weak or aligned with gradients in organism abundance, changes in concentration over time are dominated by local population dynamics. In situations where the currents are normal to these gradients, complex three-way balances arise between the local tendency, advective transport, and the population dynamics source term. Diffusion does not appear to play a major role in these simulations. We are still in the process of analyzing these solutions, and expect to have a manuscript completed by the spring of 2000.

Data-driven simulations in the Western Gulf of Maine

We have begun data-driven simulations in the western Gulf of Maine using ECOM-3D. Our first round of numerical experiments was designed to test various configurations of the open boundary conditions for the biological state variables. Treatment of biological open boundary conditions is a complex problem, with many subtle issues. Little guidance is available in the literature, as these types of models are still in early stages of development. Our most promising results come from a scheme in which the boundary values are allowed to evolve in a quasi one-dimensional sense: at outflow, a 1-D model is reset with values that have evolved naturally in the interior; on inflow that same 1-D model evolves independently, and those values are propagated into the domain. An example snapshot from one of our simulations is shown in Figure 2. Phytoplankton concentrations are high along the coast, most significantly in Cape Cod Bay, Plymouth Harbor, Boston Harbor, and Casco Bay, where the shallow bottom allows the phytoplankton to be exposed to a higher mean light intensity. High concentrations also occur offshore northeast of Cape Ann and south of Casco Bay, in water that has been pushed away from the coast, in part due to the Merrimack and Saco River plumes. Note that nitrate is depleted in areas where these intense patches of phytoplankton have formed. Computational blooms occur in a few places along the open boundary where a mismatch between the temperature and salinity boundary conditions and the interior solution causes spurious stratification. Our efforts to improve treatment of the open boundary condition continue. However, these experiments have demonstrated the feasibility of such simulations, and we are now ready to proceed with scientific applications.

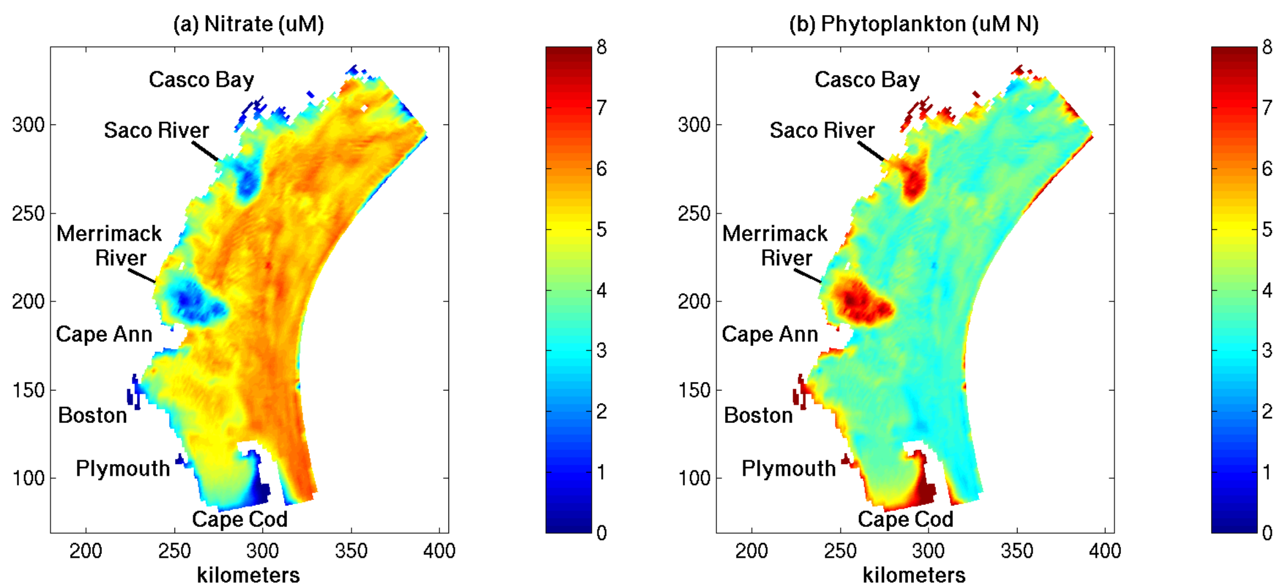

Figure 2. Simulated (a) nitrate and (b) phytoplankton distributions at 1-meter depth on 22 March 1993 in the western Gulf of Maine.

IMPACT/APPLICATIONS

(1) **Water Column Optics.** Both phytoplankton pigments and their excreta (specifically, dissolved organic material) strongly affect the transmission of light in the sea. Knowledge of the fundamental physical-biological interactions that control phytoplankton biomass variations is essential to development of the capability to predict these optical properties of the water column which can vary tremendously over short distances.

(2) **Acoustics.** While phytoplankton do not materially affect the propagation of underwater sound per se, predators higher up the food chain most certainly can. For example, certain types of gas-bearing zooplankton (e.g. siphonophores) are potential sources of reverberation in sonar systems. Because phytoplankton production is the ultimate energy source for these higher trophic levels, it is reasonable to expect that research of this type could lead to a better understanding of the patchiness of these acoustically significant organisms.

(3) **Modeling and Data Assimilation.** Realistic, data-driven models that couple physical circulation to biology, chemistry and acoustics are just now becoming feasible in the coastal ocean. As these methodologies mature, they will provide a basis for the development of real time environmental information and prediction systems which could be quite valuable to Naval operations.

TRANSITIONS

The results of this work will be made available to two major programs currently investigating plankton dynamics in this region:

(1) **U.S. Globec Georges Bank Study.** Although specifically focused on zooplankton and fish larvae, this program could benefit from information obtained here because phytoplankton are the ultimate source of nutrition for these higher trophic levels.

(2) **ECOHAB-GOM.** This effort is aimed at understanding blooms of the toxic dinoflagellate *Alexandrium*, spp. which are known to cause paralytic shellfish poisoning (PSP). Despite the fact that *Alexandrium* is generally a small component of the total phytoplankton biomass, our research may help to provide a larger ecosystem context for interpretation of their results.

RELATED PROJECTS

1 - Dr. McGillicuddy is a PI in the U.S. Globec Georges Bank program, in which he is modeling the population dynamics of *Calanus finmarchicus* and *Pseudocalanus*, spp.

2 - Dr. McGillicuddy is also involved in ECOHAB-GOM, in which he is using 3-D coupled models to examine the physical-biological interactions controlling *Alexandrium* blooms.

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